Technical Memo

ANL/EES-TM-179

TECHNOLOGY ASSESSMENT OF SOLAR ENERGY SYSTEMS:

AN ANALYSIS OF DIFFERENCES IN COST AND DIRECT AND INDIRECT AIR POLLUTANT EMISSIONS, EMPLOYMENT, AND INPUT ENERGY REQUIREMENTS BETWEEN TWO SOLAR ENERGY SCENARIOS

ARGONNE NATIONAL LABORATORY
Energy and Environmental Systems Division

prepared for
U. S. DEPARTMENT OF ENERGY
under Contract W-31-109-Eng-38

This informal report presents preliminary results of ongoing work or work that is more limited in scope and depth than that described in formal reports issued by the Energy and Environmental Systems Division.

Printed in the United States of America. Available from National Technical Information Service, U. S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161.

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by

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Energy and Environmental Systems Division
Integrated Assessments and Policy Evaluation Group

November 1981

work sponsored by

U.S. DEPARTMENT OF ENERGY
Assistant Secretary for Environmental Protection,
Safety, and Emergency Preparedness
Office of Environmental Programs

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PREFACE

The Technology Assessment Division in the Office of the Assistant Secretary for Environmental Protection, Safety, and Emergency Preparedness (formerly Office of Assistant Secretary for Environment), Department of Energy (DOE), has conducted a program entitled "Technology Assessment of Solar Energy" (TASE), which is under the guidance of Gregory D'Alessio. The goal of TASE is to determine the long-term environmental and socioeconomic effects of solar energy systems and selected nonsolar technologies. The solar technologies included in TASE are those providing domestic heating, cooling, and water heating; industrial process heat, both steam and hot air, from biomass and direct solar energy; electricity generation from wind, photovoltaics, and thermal solar energy; ethanol production from biomass; low-Btu gas production from anaerobic digestion and pyrolysis; and cogeneration of steam and electricity from pulp and paper residues.

The present report evaluates the differences between previously defined high- and low-solar scenarios on the basis of capital, operation and maintenance, and fuel cost; direct and indirect employment; emissions of SO_x, NO_x, and particulates; and energy use. Sensitivity studies on the scenarios both test the importance of some assumptions and indicate alternative paths to the utilization of renewable energy resources, paths with fewer adverse effects than the 14-quad scenario as currently defined.

A related report - "Technology Assessment of Solar Energy Systems: An Analysis of Direct and Indirect Cost, Air Pollutant Emissions, Employment, and Input Energy Requirements of Solar Energy Options," ANL/EES-TM-178, by J. Buehring et al. - complements and forms a basis for the work presented here. This companion report compares the economic, environmental, and energy-use impacts of competing solar and nonsolar energy systems for producing 10^{12} Btu of useful energy output.

For more information on the research reported here, contact Loren Habegger, Energy and Environmental Systems Division, Argonne National Laboratory.

ACKNOWLEDGMENTS

The authors would like to thank Gregory D'Alessio of DOE, Terry Surles of Argonne National Laboratory, and Yale Schiffman of MITRE Corp. for their contributions and support in preparing this report.

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EXECUTIVE SUMMARY

As part of the Technology Assessment of Solar Energy (TASE) program, a number of solar technologies were characterized by various national laboratories in terms of size; material and labor requirements for operation, maintenance, and construction; fuel requirements; and pollutant output.[1] A previous report[2] compared energy systems that incorporated those technologies, on the basis of total annualized cost, employment, emissions of air pollutants, and input energy requirements. In the present report, the effects of deploying those technologies in significant amounts is further interpreted by embedding the systems into two solar scenarios for the year 2000. A 6.0-quad* solar scenario represents "business as usual," and a 14.2-quad solar scenario represents a "maximum practical growth" scenario, as defined in previous TASE reports.[3] Both are part of a 101-quad national scenario derived from the TASE 118-quad scenario by reducing utility electricity generation to a level consistent with the 1980 DOE/EIA Annual Report to Congress. Table 1 shows the useful and intermediate solar energy outputs from the 14-quad scenario and the equivalent energy from the 6-quad scenario. Figure 1 shows the results over time in primary energy consumed. The remaining 87 quads in the overall 101-quad scenario do not change between the two solar scenarios, and therefore do not contribute to the differences. Finally, several sensitivity studies on the 14-quad scenario test the sensitivity of the results to certain assumptions, and indicate how some of the adverse effects of rapid solar development can be mitigated and the positive effects enhanced.

It must be emphasized that there is a great deal of variation in the technology characterizations, and in the energy use and indirect air pollution coefficients in the input-output table. Only indirect air pollution associated with the combustion of fuels is considered. According to EPA's 1978 estimates,[4] combustion accounts for over 95% of all NO_x emissions and about 85% of SO_x emissions, but less than half of total particulate emissions. The input-output table itself is from 1972.

The viewpoint taken in this study is that of an impartial observer looking at the costs and impacts associated with the construction and operation and maintenance (O&M) of these systems. The intended audience for the information is the policy maker, analyst, or legislator concerned with the taxation, regulation, or promotion of energy technologies. It is not intended as a decision vehicle for energy consumers or utilities, who have other concerns: most industries hope for a real return in capital expenditures of over 3.4%; utilities must worry about the effects of current taxation policies; all must worry about the uncertainties associated with new technologies and about the possible obsolescence of a capital-intensive technology.

SIX- AND FOURTEEN-QUAD SOLAR SCENARIOS

Differences between the 6- and 14-quad solar scenarios in cost, employment, indirect and ancillary energy use, and air pollutant emissions are

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*Quadrillion (10^{15}) Btu of fossil-fuel equivalents, i.e., primary fossil fuel displaced.

Table 1 Useful and Intermediate Energy Outputs (10^{15} Btu) for the High- and Low-Solar Scenarios

Energy Use	6-Quad[a] Scenario: Solar plus Conventional		14-Quad Scenario	
Useful Energy				
Space Heating	1.30		1.36	
Active solar heat		0.19		0.38
Active solar H&C		0.06		0.15
Passive solar heat		0.09		0.44
Woodstoves		0.09		0.15
Electric furnace		0.17		0
Electric heat pump		0.36		0
Gas furnace		0.21		0
Electric furnace - backup		0.07		0.24
Oil furnace		0.06		0
Water Heating	0.49		0.49	
Gas water heater		0.06		0
Active solar		0.16		0.33
Electric		0.19		0
Electric backup		0.08		0.17
IPH - Steam	2.78		2.82	
Solar IPH - low temp.		0.23		0.46
Solar IPH - med. temp.		0.34		0.67
Coal boiler - med.		0.94		0
HBTU gas boiler		0.95		0
MSW boiler		0.06		0.17
Wood boiler - large		0		0.28
Wood boiler - med.		0.07		0.28
Low-Btu gas boiler		0.14		0.80
Oil boiler		0.06		0
AG RES boiler		0		0.17
Other Electricity	1.05		0.69	
Pulp & Paper Cogeneration	1.41		1.59	
Intermediate Energy				
Electricity Generated	1.98		1.24	
Low Btu coal PP		0.49		0
High Btu coal PP		0.49		0
LWR		0.61		0
Utility photovoltaics		0.04		0.8
Power tower		0.04		0.41
Utility wind		0.22		0.50
Decentralized wind		0.02		0.15
Decentralized photovoltaics		0.01		0.02
Oil PP		0.02		0
RDF (refuse derived fuel) PP		0.03		0.08
Low Btu Gas	0.31		1.23	
Ag Res pyrolysis		0.10		0.32
MSW pyrolysis		0.02		0.07
AD - municipal sludge		0.03		0.08
AD - manure		0.06		0.06
Pyrolysis - wood		0		0.68

[a]6 quads of fossil-fuel equivalent solar energy plus 8 quads of energy from new conventional facilities. The latter 8 quads are derived from solar technologies in the 14-quad scenario.

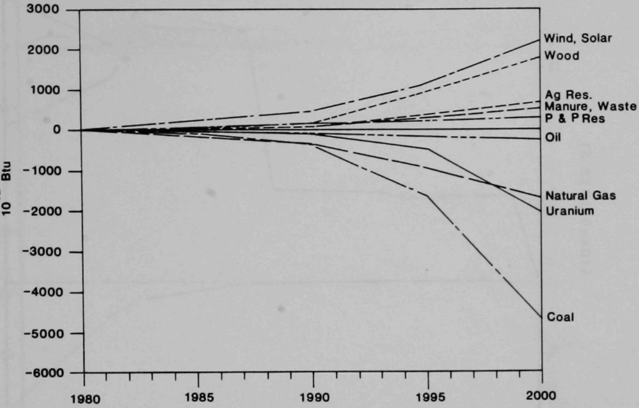

Fig. 1 Incremental Primary Energy Consumption: High-Solar Minus Low-Solar Scenario

significant. These differences are attributable to the shift in production of 8 quads of fossil-fuel-equivalent (FFE) energy (less than 4 quads of useful energy output) to solar sources from new conventional sources.

The capital-intensive nature of the solar technologies creates an increased demand for capital that reaches $20 billion (in constant 1978 dollars) per year by the year 2000 for the high-solar scenario, which is only partially offset by $9 billion per year savings in O&M cost (Fig. 2). Cumulatively, the O&M savings is just over $24 billion, while the cumulative capital penalty is over $240 billion. Computed on an annualized basis at 3.4% interest, the annual O&M plus capital cost is approximately $6.8 billion per year larger for the high-solar scenario in 2000; cumulatively, approximately $100 billion larger over the 20-year period.

The high-solar scenario leads to net reductions in SO_x and NO_x (Figs. 3 and 4) due to a decrease in direct emissions from fossil fuels, but a net increase in particulate emissions (Fig. 5), both indirect, from construction, and direct, from the combustion of wood. The SO_x reduction in 2000 amounts to 10% of the nationwide combustion-emission estimates for 1978; the NO_x reduction amounts to 4% of the nationwide combustion-emission estimates. In the year 2000 high-solar scenario, SO_x emissions due to the 14 quads of solar energy are 75% less than those from the 6 quads of solar energy and 8 quads of conventional energy in the 6-quad solar scenario. Nationally, the particulate increase is not particularly significant (2.5% of estimated nationwide combustion emissions), but local concentrations during the heating season are a serious problem.[5,6] Particulate emissions due to the 14 quads of solar energy in the high-solar scenario are 30% higher than those from the 6 quads of solar energy and 8 quads of conventional energy in the 6-quad solar scenario.

The high-solar scenario requires an additional 1.1×10^6 employees per year by the year 2000. Over 600,000 of these employees are employed

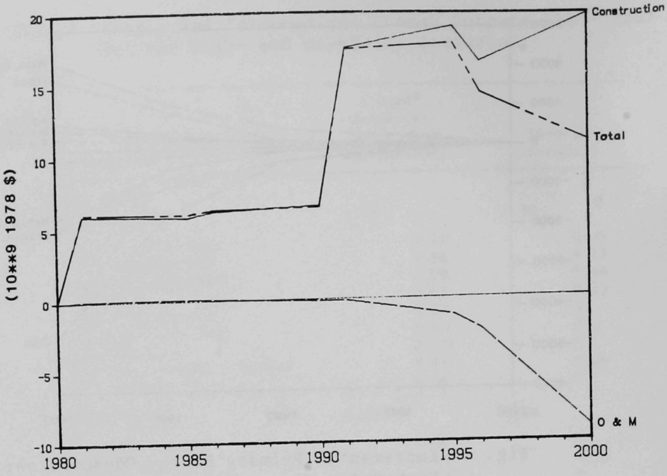

Fig. 2 Incremental Costs of Assumed Scenarios: High-Solar Minus Low-Solar Scenario

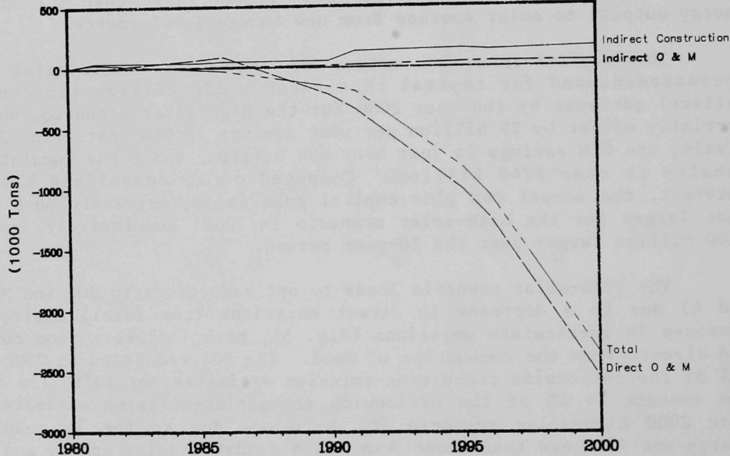

Fig. 3 Incremental SO_x Emissions: High-Solar Minus Low-Solar Scenario

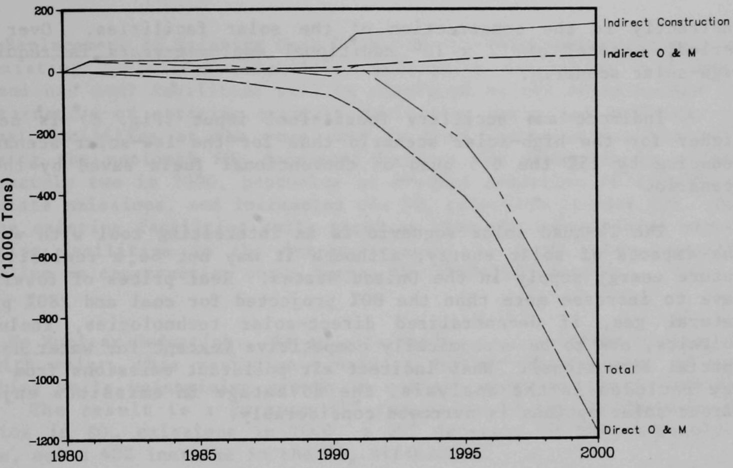

Fig. 4 Incremental NO_x Emissions: High-Solar Minus Low-Solar Scenario

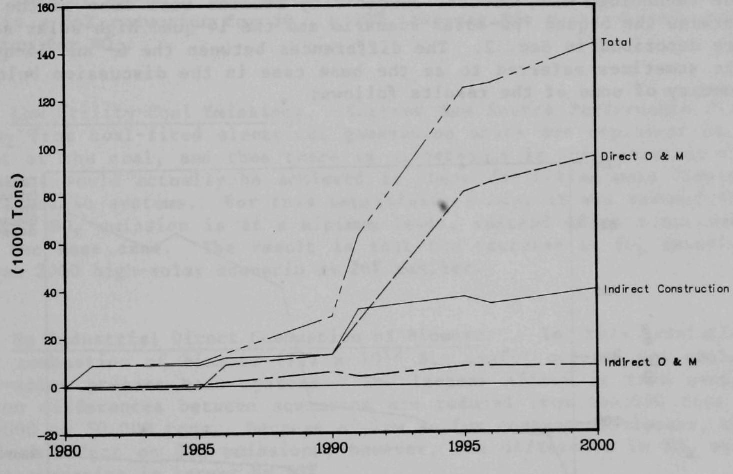

Fig. 5 Incremental Particulate Emissions: High-Solar Minus Low-Solar Scenario

indirectly in the construction of the solar facilities. Over the 20-year period, a total of 12 x 10^6 additional employee-years is required for the high-solar scenario.

Indirect and ancillary fossil-fuel input (Fig. 6) is nearly 1 quad higher for the high-solar scenario than for the low-solar scenario in 2000, reducing by 15% the 6.5 quad of conventional fuels saved by the high-solar scenario.

The 14-quad solar scenario is an interesting tool with which to study the impacts of solar energy, although it may not be a realistic picture of future energy supply in the United States. Real prices of fossil fuels will have to increase more than the 80% projected for coal and 280% projected for natural gas, if decentralized direct-solar technologies, including photovoltaics, are to be economically competitive (except for water heating, or in special situations). When indirect air pollutant emissions from construction are included in the analysis, the advantage in emissions enjoyed by the direct-solar options is narrowed considerably.

SENSITIVITY STUDIES

To investigate the sensitivity of the scenario results to assumptions in the technology characterizations, the input-output table coefficients, and the technology mix, several sensitivity studies were done on the differences between the 6-quad low-solar scenario and the 14-quad high-solar scenario that are described in Sec. 2. The differences between the 6- and 14-quad scenario are sometimes referred to as the base case in the discussion below. A brief summary of some of the results follows:

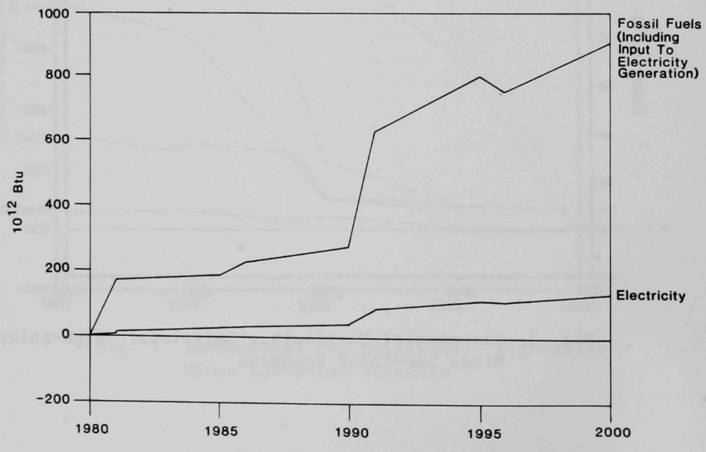

Fig. 6 Incremental Indirect Energy Inputs: High-Solar Minus Low-Solar Scenario

Replacement of Existing Coal Utility. The high-solar scenario assumes that existing coal-fired electricity generation facilities will remain in place and new coal facilities will be displaced by the solar energy systems. The alternative of retiring existing facilities early and building new conventional facilities at the same rate in both scenarios has the effect of increasing the national SO_x decrement between the scenarios by a factor of approximately two in 2000, producing an overall reduction of 150,000 tons in particulate emissions, and increasing the NO_x reduction by over 50%. However, retiring existing facilities early requires that the conventional electricity generating facilities in the 6-quad scenario be built also, resulting in $90 billion in construction costs during the 1980-2000 period.

No Nuclear Reduction. As an alternative to displacing nuclear facilities with solar, this variation considers further displacement of new coal facilities while maintaining growth in nuclear power at the 6-quad scenario level. The result is a further 33% reduction in the difference between scenarios in SO_x emissions in 2000, a 20% decrease in the particulate difference, and a 40% increase in the NO_x difference.

No Utility Coal Reduction. In this analysis, energy from utility coal is a constant in both scenarios, but nuclear energy is displaced by an equivalently greater amount. The effect on the year-2000 difference between scenarios is a 54% reduction for SO_x, a 30% increase for particulates, and a 70% reduction for NO_x.

Low Utility Coal Emissions. Current New Source Performance Standards for SO_2 from coal-fired electrical generation units are dependent on sulfur content of the coal, and thus there is uncertainty in the reduction of emissions that would actually be achieved if these facilities were displaced by solar electric systems. For this sensitivity study, it was assumed that the displaced SO_x emission is at a minimum level, instead of at a maximum level as in the base case. The result is that the decrease in SO_x emissions for the year 2000 high-solar scenario is 26% smaller.

No Industrial Direct Combustion of Biomass. In this variation the direct combustion of biomass (732×10^{12} Btu useful output) was replaced by direct-solar process heat systems. The largest effect is that particulate emission differences between scenarios are reduced from 144,000 tons in the year 2000 to 50,000 tons. Because of low sulfur content of biomass, there is a minimal effect on SO_x emissions; however, the difference in NO_x emissions between scenarios is larger by 20%.

Low Industrial Coal Emissions. The range of emission estimates for the industrial coal-fired boiler is 0.03-0.1 pound of particulates and 0.5-2.0 pounds of SO_2 per 10^6 Btu input energy. The higher estimate was used to calculate the emissions differences between the 6-quad and 14-quad solar scenarios. Using the lower emissions estimates for the coal-fired industrial boiler increases the penalty in particulate emissions by 31% to 190,000 tons per year and reduces the savings in SO_x emissions by nearly half by 2000.

More Residential Wood Stoves. Approximately 0.5 quad of space heat is shifted from active solar heating systems to wood stoves. By 2000, particulate emissions increase from 144,000 tons more than in the 6-quad solar scenario to 650,000 tons more than in the 6-quad scenario, a significant amount considering that total particulate emissions from stationary combustion are estimated to be 4.2×10^6 tons in 1978. SO_x and NO_x emissions are not significantly affected.

Passive Instead of Active Solar Space Heating Systems. Shifting to passive solar space heating systems instead of active systems makes very little difference in emissions, but a great deal of difference in capital investment and total cost over the 20-year period. By the year 2000, the difference in total construction cost for the solar scenario is reduced over 25% by using passive solar residential systems rather than active systems. The total cost increases, including operation and maintenance, are reduced by a factor of 2.

Higher Wood Stove Particulate Emissions. Particulate emissions from wood stoves are conservatively estimated for this study at 1470 tons per 10^{12} Btu of energy output. Previous characterizations have used much higher emission coefficients. The result of doubling the particulate emission coefficients for the wood stove is that particulate emission differences between the 6- and 14-quad solar scenarios increase 60%, from 144,000 tons to 231,000 tons, by 2000.

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3. *Technology Assessment of Solar Energy: Environmental and Socioeconomic Comparisons of High and Low Solar Scenarios*, U.S. Department of Energy, draft (March 1981).

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ABSTRACT

As part of the Technology Assessment of Solar Energy (TASE) program, a number of solar technologies were characterized by various national laboratories in terms of size, fuel requirements, pollutant output, and material and labor requirements for operation and maintenance and construction. Those solar technologies were embedded, along with conventional technologies, into alternative energy systems to produce useful output energy. In this report the differences between two alternative solar scenarios, a 6-quad "business as usual" and a 14-quad "maximum practical growth" scenario were evaluated for total cost and direct and indirect employment, air pollutant emissions, and energy use. An input-output table was used to estimate the indirect effects. A number of sensitivity studies illustrate the importance of some of the assumptions and indicate how some of the adverse effects of solar energy development can be mitigated. In general, the 14-quad scenario, as defined for this study, is probably not a realistic picture of future U.S. energy supply. The sensitivity studies suggest that other patterns of use of renewable energy sources will reduce the extent of adverse effects.

1 INTRODUCTION AND SCENARIO SPECIFICATION

The Office of Assistant Secretary for Environmental Protection, Safety, and Emergency Preparedness (formerly Office of Assistant Secretary for Environment) is conducting a major "Technology Assessment of Solar Energy" (TASE) program with the objective of evaluating the environmental and socioeconomic implications of the deployment of solar energy technology in the United States. Previous reports in this series characterized the direct cost and environmental residuals of 38 selected direct solar and biomass technologies.[2-11] These characterizations of technologies were then utilized to compare, on a regional and national basis, the cumulative cost and environmental implications of two alternative levels of solar implementation from 1980 to 2000.[1] In a high-solar scenario in that analysis, 14.2×10^{15} Btu (14.2 quads*) of conventional energy supply was assumed to be displaced by

*1 quad = 1 quadrillion (10^{15}) Btu.

solar technologies by the year 2000; in a low-solar, "business-as-usual" scenario, 6.0 quads of conventional energy was assumed to be displaced by solar technologies by the year 2000. (It must be noted that the 6 and 14.2 quads of the two scenarios represent fossil-fuel-equivalent energy; that is, the amount of primary fossil-fuel energy displaced by solar energy.) Both scenarios are components of alternative 118-quad total primary energy scenarios.

Additional TASE studies have considered in more detail the effects of solar technologies on, for example, air pollutant emissions,[12] employment,[13] and the increase in soil erosion accompanying the harvesting of agricultural residues for energy production.[14] A previous Argonne National Laboratory (ANL) report[15] extended previous TASE analysis to a direct comparison of alternative solar and conventional systems for producing useful space heat, water heat, industrial process steam, industrial process hot air, electricity, and cogenerated steam/electricity. Cost and direct and indirect air pollutant emissions, employment, and input energy requirements were compared in two ways for systems producing each type of useful energy:

- The impacts attributable to the production of 10^{12} Btu of useful energy were compared for each type of energy, and
- The impacts of the deployment between now and the year 2000 of 0.1 quad of additional useful energy from each of the alternative systems were evaluated.

The first method corresponds to the annual impacts from a steady-state system producing 10^{12} Btu of useful energy per year, with energy facilities being built and retired at a constant rate. Impacts due to construction, especially indirect air pollutant emissions, are more important in the second method of comparison.

In the present report, the significance of the direct and indirect parameters of the systems discussed in the previous TASE work is further interpreted through the examination of cumulative effects of deploying these systems at a level that meets a substantial fraction of future energy needs. The differences between the 6-quad and 14-quad scenarios were studied. These scenarios, as listed in Tables 1.1 and 1.2, are similar to those defined in previous TASE analyses, with the exception that the year-2000 total primary energy has been reduced from 118 quad to 101 quad by reducing utility electricity generation from new coal facilities to a level consistent with the 1980 DOE/EIA Annual Report to Congress.[16]

The indirect employment, energy-use, and air-pollutant differences between the scenarios are not, and should not be, interpreted as net changes in the economy as a whole. They are, rather, the differences in employment, energy use, and air-pollutant emissions attributable to the construction and operation and maintenance (O&M) of the energy systems involved. There are certainly changes in the rest of the economy, because of the competition for capital, changes in demand for certain goods and services, and changes in the cost and hence price of energy. What those changes are, and whether there is a net effect on GNP, are issues that are not addressed in this report. The scenarios were defined early in the TASE program and are used here for reasons of continuity with previous TASE studies. The scenarios include a substantial

Table 1.1 National Consumption of Primary Energy in 1975 and 2000 under the 6- and 14-Quad Solar Scenarios

Energy Source	Fossil-Fuel Equivalents, 10^{12} Btu 1975	2000 (Q6)	2000 (Q14)
Electric Utility	20,014	40,408	38,008
Coal	9,107	23,135	20,448
Old	9,107	9,107	9,107
New	0	14,028	11,341
Oil	3,168	668	602
Old	3,168	668	602
New	0	0	0
Gas	3,192	512	564
Nuclear	1,774	11,131	9,245
Solar	0	799	2,959
Wind	0	602	1,484
Photovoltaic	0	99	233
Thermal	0	99	1,242
Geothermal	42	532	536
Hydroelectricity	2,709	3,631	3,654
Refuse Derived Fuel/ Biomass	23	89	252
Industrial (Nonelectric)	10,627	20,970	21,884
Coal	1,391	6,847	5,471
Old	1,391	408	382
New	0	6,439	5,090
Oil	1,345	1,551	1,465
Gas	6,234	8,727	7,441
Solar	1,634	3,756	7,254
Direct	0	1,033	2,065
Biomass Heat	1,624	2,504	3,933
Biomass Gas	10	219	1,256
Residential/Commercial	12,750	13,171	15,007
Oil	4,811	2,489	2,381
Gas	7,671	9,300	8,838
Coal	169	0	0
Solar	100	1,382	3,789
Direct	0	898	2,000
Passive	0	200	1,001
Photovoltaic	0	34	51
Biomass	100	199	299
Wind	0	50	437
Transportation (Oil)	17,960	18,513	18,521
Coal (Synfuels)[a]	0	(2,716)[a]	(2,716)[a]
Coal (Synfuel Conversion Losses)	0	2,118	2,118
Alcohol[a]	0	(381)[a]	(381)[a]
Other Feedstocks	6,003	6,260	6,260
Total	67,331	101,440	101,798

[a]Not added to the total, because the values are included in the oil and gas figures in the other sectors.

Table 1.2 National Industrial and Residential/Commercial Consumption of Solar and Biomass Energy in 1975 and 2000 under the 6- and 14-Quad Solar Scenarios

Solar/Biomass Energy Use	Fossil Fuel Equivalents, 10^{12} Btu 1975	2000 (Q6)	2000 (Q14)
Industrial Process Heat	1634	3756	7255
Direct Solar	0	1033	2065
Total Energy Systems	0	309	618
Low Temperature	0	114	227
Medium Temperature	0	611	1222
Biomass	1624	2504	3952
Municipal Waste	23	90	248
Wood-Fired Boiler			
Large	0	0	408
Medium	0	102	408
Agricultural Residual Boiler	0	0	270
Cogeneration from Pulp and Paper Wastes	1601	2312	2599
Biomass Gas	10	219	1256
Anaerobic Digestion			
Sewage Sludge	0	31	86
Manure	0	66	66
Pyrolysis			
Municipal Waste	10	19	74
Agricultural Waste	0	100	328
Wood	0	0	699
Residential/Commercial	100	1382	3789
Active Heating	0	415	960
Active Heating and Cooling	0	142	331
Passive Heating	0	200	1001
Hot Water	0	341	710
Wind	0	50	437
Photovoltaic	0	34	51
Woodstoves	100	200	299

contribution of energy from technologies that do not appear likely to receive extensive development, on the basis of results of earlier TASE studies.[15] In particular, the active solar heating and active solar heating and cooling systems provide 0.25 quad of useful energy in the 6-quad scenario and 0.53 quad in the 14-quad scenario. That seems excessive for systems with projected costs so much greater than any other heating system. As characterized, the natural gas furnace and water heater have the lowest cost except for the heat pump, and the lowest air-pollutant emissions. If natural gas is available in 2000 at the projected price of slightly over 2.5 times the 1980 price, one would expect natural gas to retain its importance in space heating.

In the industrial sector, substantial amounts of steam from direct-solar industrial process heat (IPH) systems are projected (1.13 quad in the 14-quad scenario, 0.57 quad in the 6-quad scenario). Those technologies are high in total annualized cost, and particularly high in capital cost. Using the costs projected in the technology characterizations, the appeal of the direct-solar systems would be limited to those localities with strict air-pollution regulations and no availability of natural gas. Energy from wood and agriculture residues in the 6- and 14-quad scenarios appears to be well within possible ranges calculated by others.[17,18]

The TASE 14-quad scenario includes approximately 1.1 quad of electricity generated by solar facilities. For electricity generation, cost comparisons are even more difficult than for industrial or residential/commercial systems. Not only do taxing and regulatory practices have an effect, but the question of whether and how much the new facility contributes to the reliability of the system is important. (In general, the firm-capacity equivalent* of the solar facilities is less than the firm-capacity equivalent of the alternative coal or LWR facilities. It is analogous to, but much more complicated than, having back-up electric heat for a direct-solar space heating system. The subject is treated at length, for wind systems, in Ref. 19.)

The 1.1 quad of electricity generated by solar facilities represents 8.5% of the total electricity generated in the 14-quad solar scenario. That means that some utilities would have considerably more than 8.5% penetration by solar energy. For the wind systems studied in Ref. 19, incremental firm-capacity equivalents diminish as the penetration of wind-driven generating capacity rises above 10%; additional penetration by wind systems must be justified primarily by savings on fuel and variable O&M costs. One can expect the same effect with the solar thermal and photovoltaic systems. The power tower, as characterized, has six hours of storage but the other solar facilities are assumed to have no storage. Under current law,[20] utilities must buy electricity generated by decentralized wind and photovoltaic facilities at the utilities' net avoided cost. If the decentralized power producer has agreed to provide energy through a legally enforceable obligation, a capacity credit must be included in the rate paid by the utility. If the energy is provided on an "as available" basis, the payment by the utility is based only on the utilities' avoided fuel and variable O&M cost.[21] In no case is the payment as large as the cost of providing the same amount of energy from a facility with a larger firm-capacity equivalent. The result is that the annualized cost per 10^{12} Btu generated shown in Table 1.3 is understated, because the facilities are not always available when needed. The less reliable the facility is, the more the true cost is understated. Recalculating the costs for each type of generating facility, on the basis of some assumed mix of facilities in an average system, is an interesting problem, but beyond the scope of this study.

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*Firm-capacity equivalent is the amount of dependable capacity that could hypothetically be removed from the generating system after adding a new generating unit, to maintain the same loss-of-load probability as in the original system. It is a function of the characteristics of the original generating system and of the added capacity.

Table 1.3 Cost Per 10^{12} Btu of Electricity Generated

System	Annualized Construction Cost ($\$10^6$)[a]	O&M Cost ($\$10^6$)[a]	Total Annualized Cost ($\$10^6$)[a]
Light Water Reactor	2.3	1.8	4.1
High-Btu Coal Power Plant	1.5	11.0	12.5
Low-Btu Coal Power Plant	1.5	8.6	10.1
Solar Power Tower	5.9	1.5	7.4
Centralized Photovoltaic	6.5	2.5	9.0
Centralized Wind	4.9	2.3	7.2
Decentralized Wind	17.0	13.0	30.0
Decentralized Photovoltaic	33.0	5.5	38.5

[a]Costs are in 1978 dollars.

Source: Ref. 15.

There is also a disincentive toward capital-intensive technologies for both utilities and consumers because of the risk of committing large amounts of resources to a technology that may become obsolete or be unreliable. Not only are the decentralized systems extremely expensive compared with the other options, but their total emissions of air pollutants are very high; only the coal power plants are as bad or worse. One percent of total generation in the year 2000 seems high for systems with the disadvantages associated with the decentralized wind and photovoltaic systems. The centralized wind, photovoltaic, and power tower facilities have competitive annualized costs, but considering the problems mentioned above, 7.5% of total generation may be optimistic.

The approach used in this analysis is to evaluate only the 14 quad of primary energy that is delivered by the solar energy systems in the high-solar scenario and compare it to the equivalent 6 quad of solar plus 8 quad of conventional energy in the low-solar scenario.

The scenarios were structured for equivalence in useful energy, which is approximately 7 quad for the 14 quad of fossil-fuel equivalent energy (FFE). Since some assumptions are necessary about the technologies displaced by solar energy in order to calculate FFEs, a unit of FFE is not a constant unit of energy. Since the original scenarios were not specified in terms of useful energy, some judicious planning of the energy network was necessary to ensure equivalency. Figure 1.1 shows the difference in primary energy inputs between the two scenarios. The high-solar scenario shows a saving of 4.5 quad of coal, just over 1.5 quad each of raw uranium and natural gas, and a small amount of oil. There is a difference of just over 2 quad of solar and wind energy, but that is at an efficiency of 1.0. Wind is higher by 1.75 quad, and agricultural residues by not quite 0.75 quad, in the high-solar scenario. Cogeneration from pulp and paper residues is an established technology that is assumed to provide about 1.5 quad of useful energy in both scenarios.

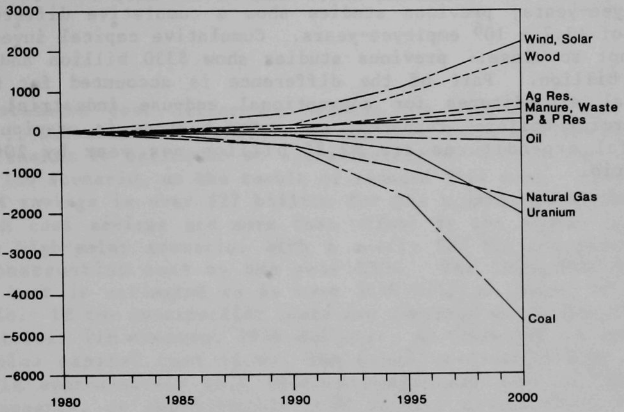

Fig. 1.1 Incremental Primary Energy Consumption: High-Solar Minus Low-Solar Scenario

Cost, direct and indirect air-pollutant emissions, and direct and indirect employment for the 6- and 14-quad scenarios have been evaluated in previous TASE studies.[1] Previous results and the results presented in this report are not identical, for several reasons:

- The scenarios for this study are embedded in 101-quad FFE scenarios rather than 118-quad scenarios.
- Although the final year-2000 energy use is similar between the two pairs of scenarios, the growth is more exponential in the earlier scenarios. A sensitivity study in Sec. 3 of this report shows the results of scenarios with growth rates that more closely approximate growth rates of the previous TASE scenarios.
- A different input/output table and associated employment, energy use, and air-pollutant emissions are used for this study. More information about the methodology used for this analysis can be found in Ref. 15.
- Technology characterizations were reviewed as part of this analysis, and some relatively minor changes were made. In addition, more conventional technologies were characterized with inclusion of their end use technologies, e.g., furnaces and water heaters.

Despite these differences in methodology and scenarios, differences between the 14-quad and the 6-quad scenarios are quite similar in this and the previous studies. For example, previous TASE studies show a difference in capital expenditures of $22 billion per year in the year 2000, whereas this analysis shows a difference of \$20 billion per year. The current analysis shows a cumulative difference in employment from 1980 to 2000 of 12×10^6 employee-years; previous studies show a cumulative difference from 1975 to 2000 of 13.7×10^6 employee-years. Cumulative capital investment differences are not so close: previous studies show \$330 billion and this study shows \$240 billion. Part of the difference is accounted for by the absence of capital expenditures for conventional end-use industrial and residential/commercial boilers, furnaces, and water heaters in previous studies. Those capital expenditures are \$2.25 billion per year by 2000 in the 6-quad scenario.

2 EVALUATION OF THE DIFFERENCES BETWEEN THE 6-QUAD AND 14-QUAD SOLAR SCENARIOS

2.1 COST

The estimated cost difference between the high-solar and low-solar scenarios is illustrated in Fig. 2.1. By the year 2000, the O&M cost for the high-solar scenario is estimated at approximately $9 billion per year lower than for the low scenario, as the result of reduced fuel cost. The cumulative 1980-2000 O&M savings is over $27 billion for the high-solar scenario. However, the O&M cost savings are more than offset by the higher construction costs in the high-solar scenario, with a nearly $20 billion yearly differential in construction cost by the year 2000. The 1980-2000 cumulative construction cost is estimated to be over $240 billion larger for the high-solar scenario. If the construction costs are computed on an annualized basis with 3.4% interest (in constant 1978 dollars), as described in Ref. 15, the annual O&M plus capital cost (i.e., the actual estimated cost of energy production) is approximately $6.8 billion larger per year in 2000 for the high-solar scenario, or approximately $100 billion larger cumulatively over the 1980-2000 time period.

2.2 EMPLOYMENT

Employment differences between the high- and low-solar scenarios are shown in Fig. 2.2. The high-solar scenario is more labor-intensive in all categories: direct and indirect O&M and direct and indirect construction. By the year 2000, the high-solar scenario is projected to require approximately

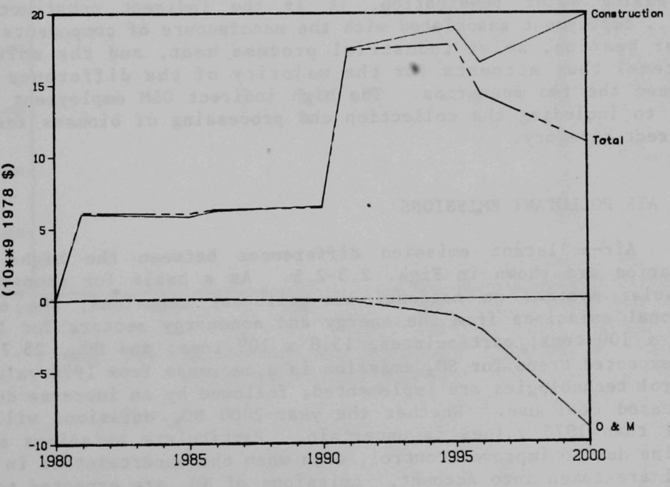

Fig. 2.1 Incremental Cost: High-Solar Minus Low-Solar Scenario

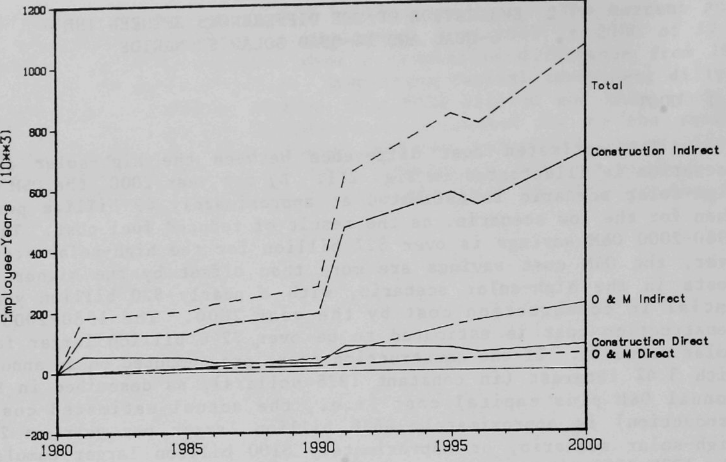

Fig. 2.2 Incremental Employment: High-Solar Minus Low-Solar Scenario

an additional 135,000 employees per year, or 1.7 x 10^6 employee-years cumulatively over the 1980-2000 period, for direct construction and O&M of the facilities. The greatest effect is the estimated indirect employment of nearly 10^6 employees per year in the year 2000, or over 10 x 10^6 employee-years cumulatively in the 20-year period analyzed. In this period of rapidly increasing solar penetration, it is the indirect construction employment (i.e., employment associated with the manufacture of components for the direct solar heating, solar industrial process heat, and the solar power tower systems) that accounts for the majority of the difference in employment between the two scenarios. The high indirect O&M employment is also due in part to including the collection and processing of biomass feedstocks in the indirect category.

2.3 AIR POLLUTANT EMISSIONS

Air-pollutant emission differences between the high- and low-solar scenarios are shown in Figs. 2.3-2.5. As a basis for comparing the impact of solar systems on national air-pollutant emissions, the estimated total national emissions from the energy and nonenergy sectors for 1978 are: SO_x, 29.8 x 10^6 tons; particulates, 13.8 x 10^6 tons; and NO_x, 25.7 x 10^6 tons.[22] The expected trend for SO_x emission is a decrease from 1978 values as improved control technologies are implemented, followed by an increase due primarily to increased coal use. Whether the year-2000 SO_x emissions will be higher or lower than 1978 values is uncertain. Particulate emissions are expected to decline due to improved control, even when the uncertainties in actual control level are taken into account. Emissions of NO_x are expected to increase over time due to a lower percentage reduction in NO_x emissions than in SO_x or particulate emissions. Overall national emissions of these three pollutants in 2000 are not expected to differ greatly from emissions in 1978.

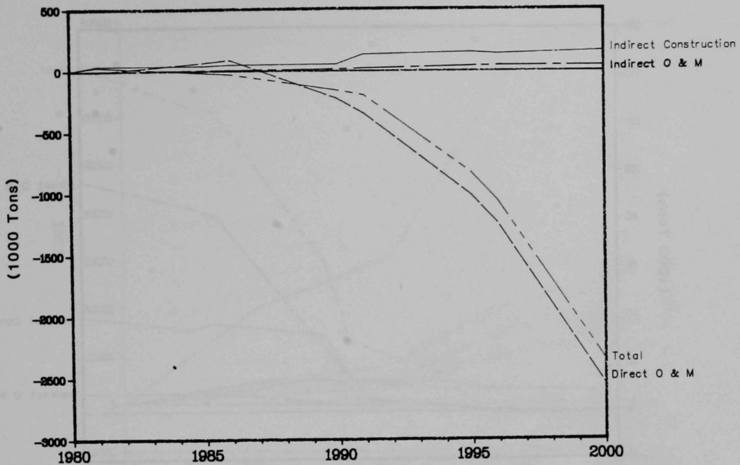

Fig. 2.3 Incremental SO_x Emissions: High-Solar Minus Low-Solar Scenario

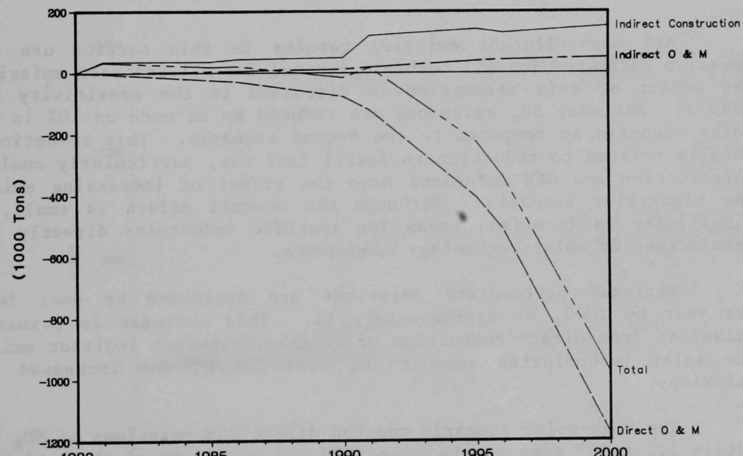

Fig. 2.4 Incremental NO_x Emissions: High-Solar Minus Low-Solar Scenario

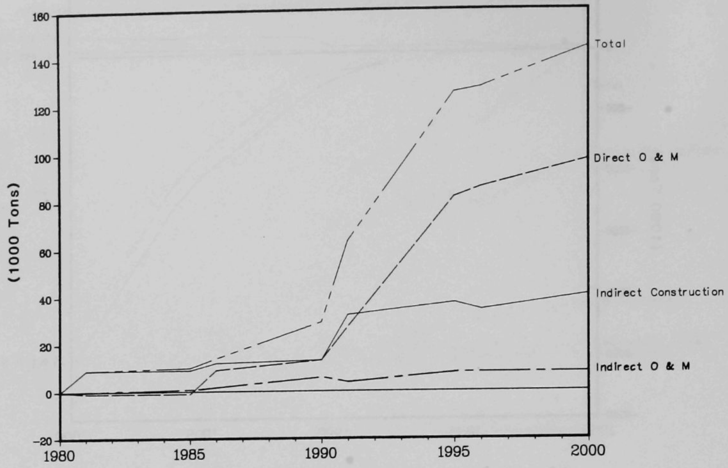

Fig. 2.5 Incremental Particulate Emissions: High-Solar Minus Low-Solar Scenario

All air-pollutant emission results in this section use the maximum emission estimates for all technologies and for all indirect emission sources. The effect of this assumption is discussed in the sensitivity analysis in Sec. 3. National SO_x emissions are reduced by as much as 10% in the 14-quad solar scenario as compared to the 6-quad scenario. This reduction is almost totally related to reduction in fossil fuel use, particularly coal. Indirect construction and O&M emissions have the effect of increasing emissions from the high-solar scenario. Although the overall effect is small, it may be significant in localized areas for specific industries directly involved in manufacture of solar technology components.

National particulate emissions are increased by over 140,000 tons per year by 2000, or approximately 1%. This increase is primarily due to emissions from direct combustion of biomass, although indirect emissions from the solar technologies account for over 25% of the increased particulate emissions.

The high-solar scenario reduced direct O&M emissions of NO_x by approximately 1.2×10^6 tons by the year 2000, or nearly 5% of the national total in 1978. Indirect construction emissions of NO_x are increased 0.2×10^6 tons, or 1% of the national total, resulting in a net reduction of 4% of the national total.

The differences in indirect SO_x and particulate emissions (from O&M plus construction) between the high- and low-solar scenarios for selected BEA industrial categories are shown in Figs. 2.6 and 2.7. (Table 2.1 shows a key to the BEA codes.) The industries shown account for 86% of the difference in particulates and 84% of the difference in SO_x emissions in 2000. Indirect emissions for both O&M and construction are greater for the high-solar

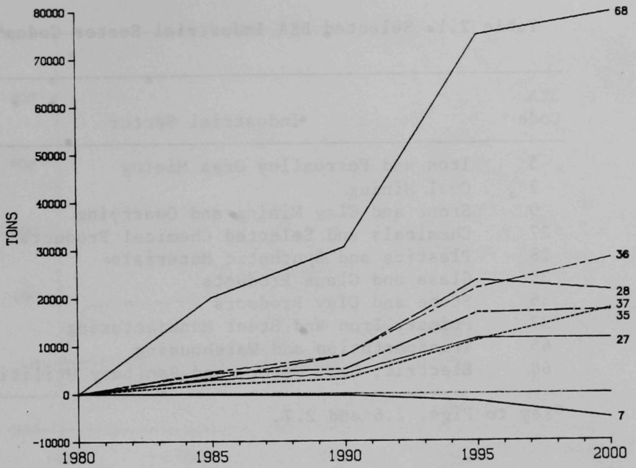

Fig. 2.6 Incremental Indirect SO_x Emissions, by BEA Industry: High-Solar Minus Low-Solar Scenario (see Table 2.1 for key to BEA Codes)

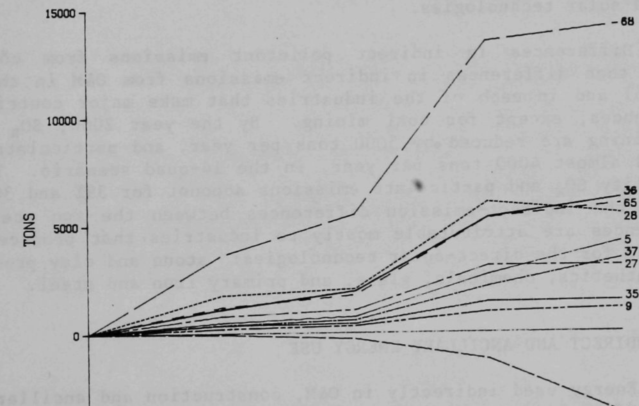

Fig. 2.7 Incremental Indirect Particulate Emissions, by BEA Industry: High-Solar Minus Low-Solar Scenario (see Table 2.1 for key to BEA Codes)

Table 2.1 Selected BEA Industrial Sector Codes[a]

BEA Code	Industrial Sector
5	Iron and Ferroalloy Ores Mining
7	Coal Mining
9	Stone and Clay Mining and Quarrying
27	Chemicals and Selected Chemical Products
28	Plastics and Synthetic Materials
35	Glass and Glass Products
36	Stone and Clay Products
37	Primary Iron and Steel Manufacturing
65	Transportation and Warehousing
68	Electric, Gas, Water, and Sanitary Utilities

[a]Key to Figs. 2.6 and 2.7.

scenario than for the low, throughout the time period. In general, one would expect both indirect energy use and indirect air-pollutant emissions to vary directly with the O&M cost. In this case, however, maintenance of the solar technologies requires the same energy-intensive materials required for construction, and maintenace is a larger fraction of the total O&M cost for the solar technologies.

Differences in indirect pollutant emissions from construction are higher than differences in indirect emissions from O&M in the total (Figs. 2.3-2.5) and in each of the industries that make major contributions to the differences, except for coal mining. By the year 2000, SO_x emissions from coal mining are reduced by 5000 tons per year, and particulate emissions are reduced almost 4000 tons per year, in the 14-quad scenario. The differences in utility SO_x and particulate emissions account for 39% and 30%, respectively, of the indirect-emission differences between the two scenarios. Other differences are attributable mostly to industries that produce the materials required for the direct-solar technologies: stone and clay products, plastics and synthetics, chemicals, glass, and primary iron and steel.

2.4 INDIRECT AND ANCILLARY ENERGY USE

Energy used indirectly in O&M, construction and ancillary energy input is significant compared with the output energy provided by the solar technologies. The decentralized photovoltaic system requires nearly 1 Btu of indirect fossil energy for each Btu of electricity produced. The difference in indirect and ancillary (e.g., electricity required to run a fan or pump) fossil fuel and electricity requirements are shown in Fig. 2.8. By the year 2000, approximately 0.9 quad more fossil fuel is required per year for the high-solar scenario, reducing by 15% the 6.5 quad of fossil fuel saved in direct energy input.

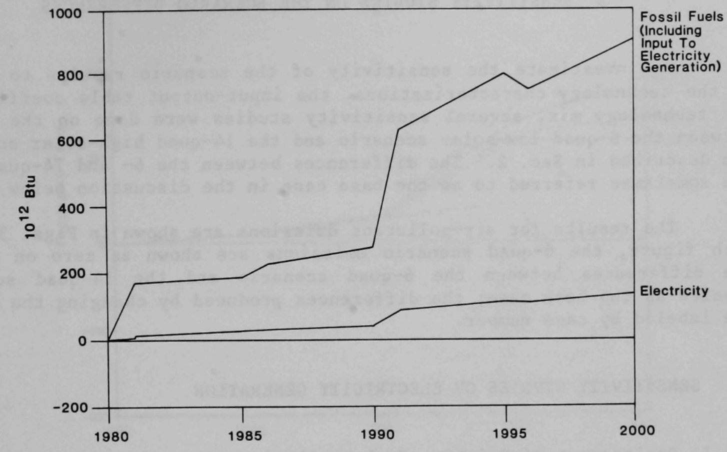

Fig. 2.8 Incremental Indirect Energy Inputs: High-Solar Minus Low-Solar Scenario

3 SENSITIVITY STUDIES ON THE SCENARIO DIFFERENCES

To investigate the sensitivity of the scenario results to assumptions in the technology characterizations, the input-output table coefficients, and the technology mix, several sensitivity studies were done on the differences between the 6-quad low-solar scenario and the 14-quad high-solar scenario that are described in Sec. 2. The differences between the 6- and 14-quad scenarios are sometimes referred to as the base case in the discussion below.

The results for air-pollutant emissions are shown in Figs. 3.1-3.9. In each figure, the 6-quad scenario emissions are shown as zero on the graphs. The differences between the 6-quad scenario and the 14-quad scenario are labeled as the base case; the differences produced by changing the assumptions are labeled by case number.

3.1 SENSITIVITY STUDIES OF ELECTRICITY GENERATION

3.1.1 Replacement of Existing Coal Facilities (Case 3)

The high-solar scenario assumed that existing coal-fired electricity generation facilities will remain in place, and new coal facilities will be displaced by the solar energy systems. The alternative of retiring existing facilities early and building new conventional facilities at the same rate in both scenarios has the effect of increasing the national SO_x decrement between the scenarios by a factor of approximately two in 2000, producing an overall reduction of 150,000 tons in particulate emissions, and increasing the NO_x reduction by over 50%.

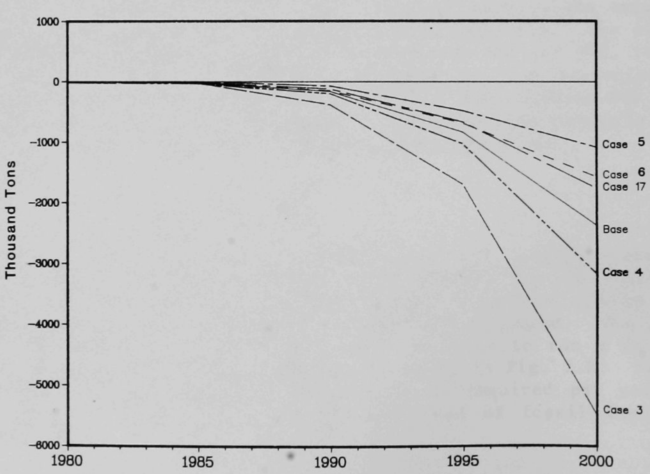

Fig. 3.1 Sensitivity Studies of Electricity Generation: Changes in Incremental SO_x Emissions

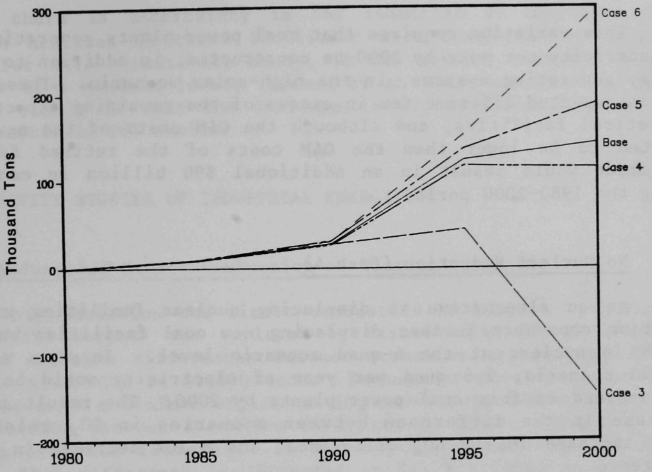

Fig. 3.2 Sensitivity Studies of Electricity Generation: Changes in Incremental Particulate Emissions

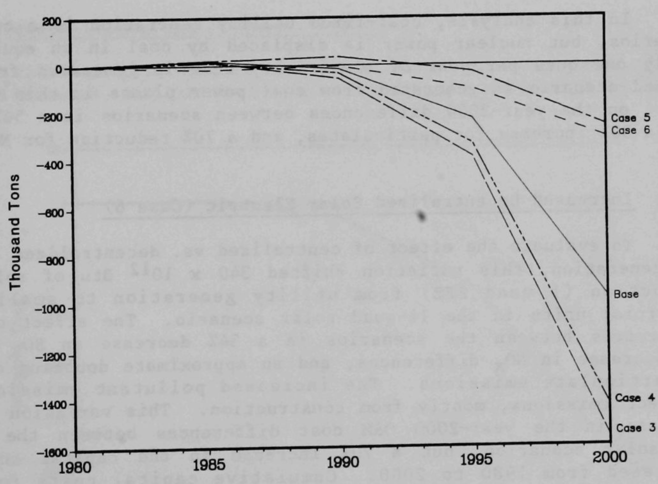

Fig. 3.3 Sensitivity Studies of Electricity Generation: Changes in Incremental NO_x Emissions

This variation requires that coal power plants generating nearly 1 quad of electricity per year by 2000 be constructed, in addition to the solar electricity generating systems, in the high-solar scenario. These new facilities have an expected lifetime far in excess of the remaining expected lifetimes of the retired facilities, and although the O&M costs of the new facilities are expected to be lower than the O&M costs of the retired facilities, early retirement would result in an additional $90 billion in construction costs during the 1980-2000 period.

3.1.2 No Nuclear Reduction (Case 4)

As an alternative to displacing nuclear facilities with solar, this variation considers further displacing new coal facilities while maintaining growth in nuclear at the 6-quad scenario level. In this variation of the 14-quad scenario, 0.6 quad per year of electricity would be generated from LWRs instead of from coal power plants by 2000. The result is a further 33% increase in the difference between scenarios in SO_x emissions in 2000, a 40% increase in the NO_x difference, and a 20% decrease in the particulate difference.

3.1.3 No Utility Coal Reduction (Case 5)

In this analysis, coal-fired utility generation is a constant in both scenarios, but nuclear power is displaced by coal in an equivalent amount. Nearly one quad per year of electricity that is generated from LWRs in the 14-quad scenario is generated from coal power plants in this variation. The effect on the year-2000 differences between scenarios is a 54% reduction for SO_x, a 30% increase for particulates, and a 70% reduction for NO_x.

3.1.4 Increased Decentralized Solar Electric (Case 6)

To evaluate the effect of centralized vs. decentralized solar electricity generation, this variation shifted 340×10^{12} Btu of solar electricity production (1 quad FFE) from utility generation to small residential/commercial units in the 14-quad solar scenario. The effect on the emission differences between the scenarios is a 34% decrease in SO_x differences, a 60% decrease in NO_x differences, and an approximate doubling of the increase in particulate emissions. The increased pollutant emissions are due to indirect emissions, mostly from construction. This variation leads to a 13% decrease in the year-2000 O&M cost differences between the low-solar and high-solar scenarios, but a 70% increase in the capital cost differences cumulated from 1980 to 2000. Cumulative capital costs for the 14-quad scenario are $244 billion more than for the 6-quad scenario, whereas cumulative capital costs for the case-6 variation are $414 billion more than for the 6-quad scenario.

3.1.5 Low Utility Coal Emissions (Case 17)

Current New Source Performance Standards for SO_x from coal-fired electrical generation units depend on the sulfur content of the coal.

Therefore, there is uncertainty in the reduction of emissions that would actually be achieved if these facilities were displaced by solar electric systems. For this sensitivity study, it was assumed that the displaced SO_x emission is at a minimum level, instead of at a maximum level as in the base case. The result is that the decrease in SO_x emissions for the year 2000 Case 17 scenario is 26% smaller.

3.2 SENSITIVITY STUDIES OF INDUSTRIAL ENERGY USE

3.2.1 No Industrial Direct Combustion of Biomass (Case 7)

In this variation the direct combustion of biomass (to produce 0.732 quad of useful output) was replaced by direct-solar process heat systems. Particulate emission differences between scenarios are reduced from 144,000 tons in the year 2000 to 50,000 tons. Because of the low sulfur content of biomass, there is a minimal effect on SO_x emissions; however, the difference in NO_x emissions between scenarios is larger by 20%. By 2000, there is a \$9-billion-per-year difference in O&M costs, in favor of the high-solar scenario. That difference is increased to \$11.5 billion in this variation. However, the cumulative capital difference (in favor of the low-solar scenario) is increased 39%, from \$244 billion to \$339 billion.

3.2.2 Increased Industrial Biomass (Case 8)

For this analysis the 0.732 quad of direct biomass combustion in 2000 is also eliminated, but it is replaced by syngas, produced from biomass and

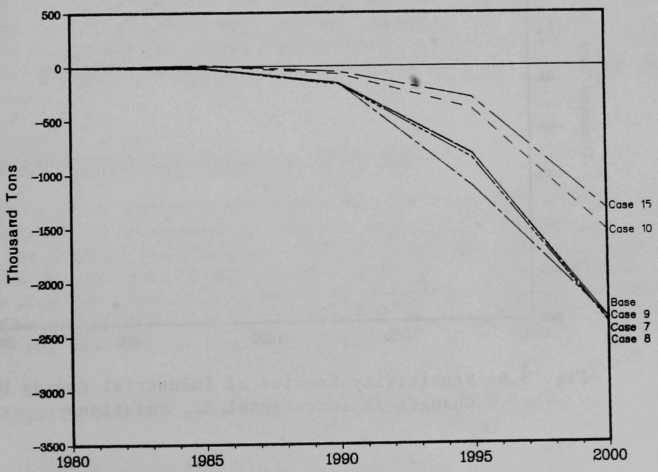

Fig. 3.4 Sensitivity Studies of Industrial Energy Use: Changes in Incremental SO_x Emissions

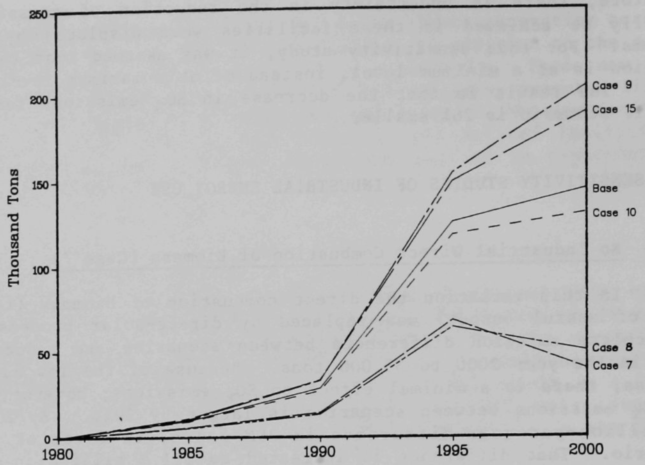

Fig. 3.5 Sensitivity Studies of Industrial Energy Use: Changes in Incremental Particulate Emissions

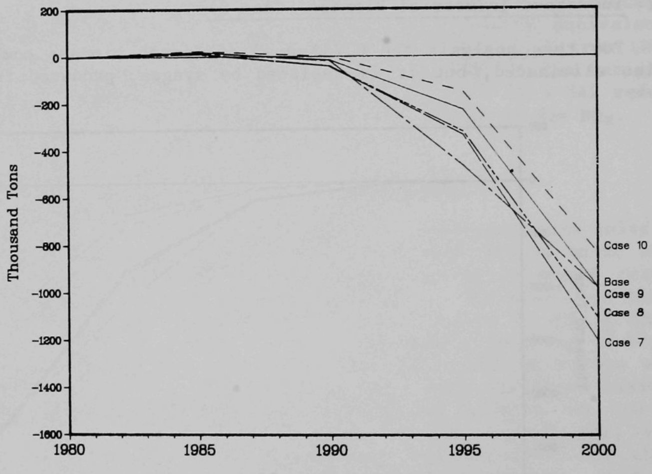

Fig. 3.6 Sensitivity Studies of Industrial Energy Use: Changes in Incremental NO_x Emissions

burned in low-Btu gas boilers. Because the chain from biomass to synthetic gas to gas boilers is less efficient than direct combustion, an additional 0.33 quad of wood and agricultural residues are required to produce the same amount of useful energy. The increment in particulate emissions between scenarios in the year 2000 is reduced from 144,000 to 50,000 tons because of the use of syngas. Also, the high-solar scenario in this variation produces about 200,000 tons less NO_x. The changes in SO_x emissions are minimal. There is little difference in the annualized capital cost, in the year 2000, between the 14-quad scenario and this variation, but there is a $1.8-billion-per-year increase in O&M costs. The difference in O&M cost in 2000 between the 6-quad scenario and this variation of the 14-quad scenario is $7.2 billion, versus $9.03 billion between the 6-quad and the original 14-quad scenarios.

3.2.3 Smaller Wood Boilers (Case 9)

The mixture of small and large industrial wood boilers was changed from half large and half medium-sized units in the 14-quad scenario to all medium-sized boilers in this variation. Revised New Source Performance Standards for particulates are less stringent for smaller boilers, which results in a 40% greater increase in particulate emissions by 2000.

3.2.4 Reduced Oil Use in Industry (Case 10)

Coal use is held at the same level in the 6-quad solar scenario and this variation of the 14-quad scenario. The new solar technologies are assumed to replace oil in the industrial sector. In this case the reduction in SO_x and NO_x emissions are 67% and 85% of the base-case reductions, respectively, and the increase in particulate emissions is slightly less. Because particulate emissions are so well controlled in the coal boiler characterized, particulate emissions actually decrease slightly with the replacement of oil with coal.

3.2.5 Low Industrial Coal Emissions (Case 15)

The range of emission estimates for the industrial coal-fired boiler is 0.03-0.1 pounds of particulates and 0.5-2.0 pounds of SO_x per 10^6 Btu input energy. The higher estimate was used to calculate the emission differences between the 6-quad and 14-quad solar scenarios. Using the lower emissions estimates for the coal-fired industrial boiler increases the penalty in particulate emissions by 31%, to 190,000 tons per year, and reduces the savings in SO_x emission by nearly half by 2000.

3.3 SENSITIVITY STUDIES OF RESIDENTIAL/COMMERCIAL ENERGY USE

3.3.1 More Residential Wood Stoves (Case 11)

Approximately 0.5 quad of space heat is shifted from active solar heating systems to wood stoves. By 2000, particulate emissions increase from

144,000 tons more than in the 6-quad solar scenario to 650,000 tons more than in the 6-quad scenario, a significant amount, considering that total particulate emissions from stationary combustion are estimated to be 4.2×10^6 tons in 1978. SO_x and NO_x emissions are not significantly affected. Cumulatively from 1980 to 2000, the construction cost increment from the 6-quad scenario to the 14-quad scenario is reduced 23%, from $244 billion to $187 billion. By 2000, however, the annual O&M savings from the high-solar scenario is reduced 30%, from $9 billion to $6.2 billion, due to the cost of wood as fuel.

3.3.2 Passive Instead of Active Solar Space Heating Systems (Case 14)

Shifting to passive solar space heating systems instead of active systems makes very little difference in emissions, but a great deal of difference in capital investment and total cost over the 20-year period (Fig. 3.10). By the year 2000, total increases in construction cost for the solar scenario are reduced more than 25% by using passive solar residential space heating rather than active systems. The incrases in total cost, including O&M, are reduced by one-half.

3.3.3 Higher Wood Stove Particulate Emissions (Case 18)

Particulate emissions from wood stoves are conservatively estimated, for this study, at 1470 tons per 10^{12} Btu of energy output. Previous characterizations have used much higher emission coefficients. The result of doubling the particulate emission coefficients for the wood stove are that the particulate emission difference between the 6- and 14-quad solar scenarios increases 60%, from 144,000 tons to 231,000 tons, by 2000.

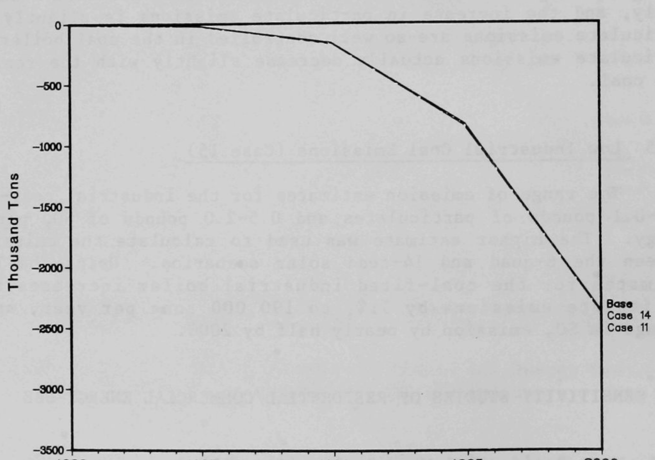

Fig. 3.7 Sensitivity Studies of Residential/Commercial Energy Use: Changes in Incremental SO_x Emissions

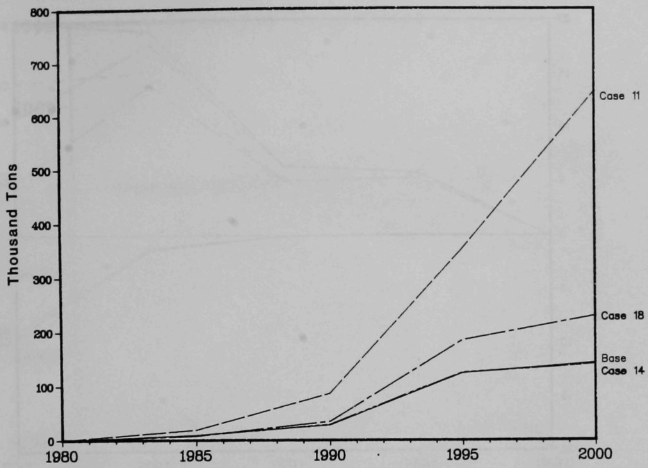

Fig. 3.8 Sensitivity Studies of Residential/Commercial Energy Use: Changes in Incremental Particulate Emissions

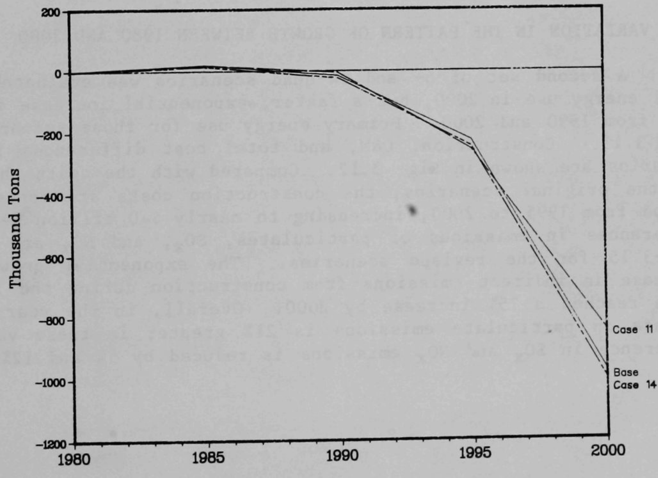

Fig. 3.9 Sensitivity Studies of Residential/Commercial Energy Use: Changes in Incremental NO_x Emissions

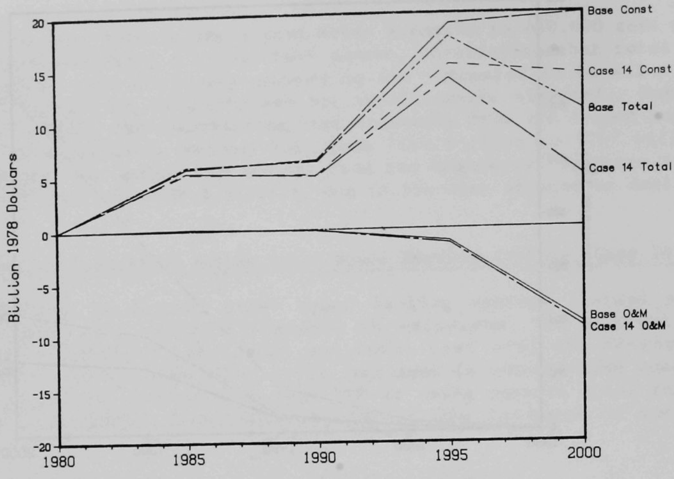

Fig. 3.10 Sensitivity Studies of Residential/Commercial Energy Use: Changes in Cost Differences in Case 14

3.4 VARIATION IN THE PATTERN OF GROWTH BETWEEN 1980 AND 2000

A second set of 6- and 14-quad scenarios was evaluated with the same total energy use in 2000, but a faster, exponential increase in solar facilities from 1990 and 2000. Primary energy use for those scenarios is shown in Fig. 3.11. Construction, O&M, and total cost differences for the revised scenarios are shown in Fig. 3.12. Compared with the costs shown in Fig. 2.1 for the original scenarios, the construction costs are concentrated in the period from 1995 to 2000, increasing to nearly $40 billion per year by 2000. Differences in emissions of particulates, SO_x, and NO_x are shown in Figs. 3.13-3.15 for the revised scenarios. The exponential growth produces an increase in indirect emissions from construction during the last few years, which reaches a 75% increase by 2000. Overall, in the year 2000, the difference in particulate emissions is 21% greater in these variations. The difference in SO_x and NO_x emissions is reduced by 5% and 12%, respectively.

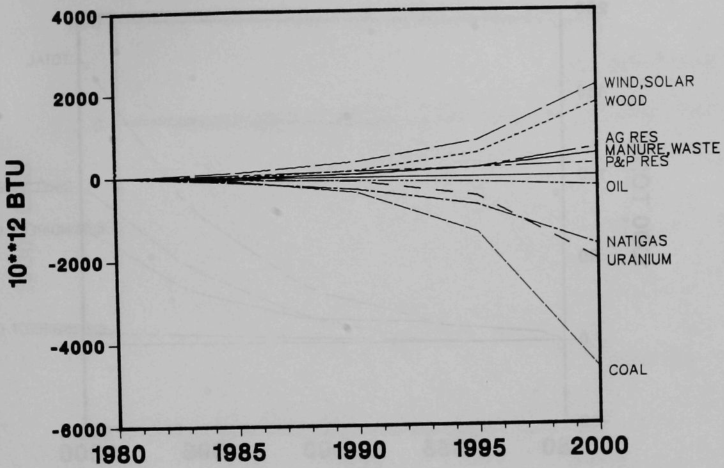

Fig. 3.11 Sensitivity Analysis of Solar Growth: Changes in Incremental Primary Energy Use

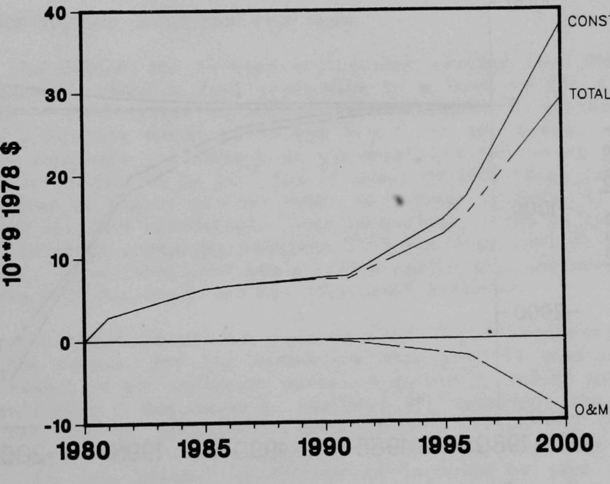

Fig. 3.12 Sensitivity Analysis of Solar Growth: Changes in Incremental Costs

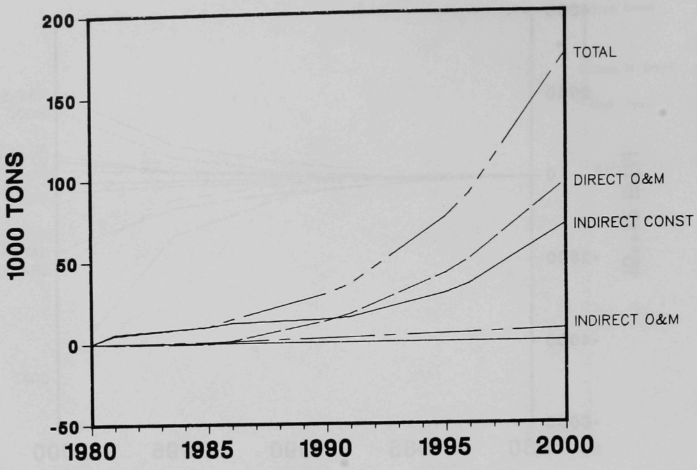

Fig. 3.13 Sensitivity Analysis of Solar Growth: Changes in Incremental Particulate Emissions

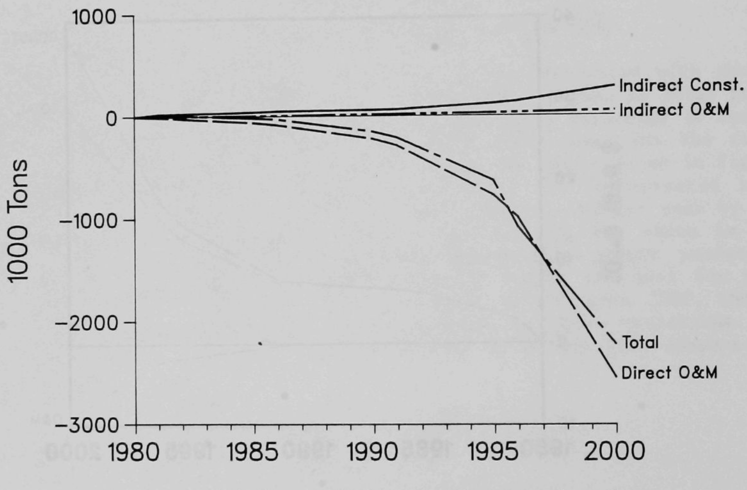

Fig. 3.14 Sensitivity Analysis of Solar Growth: Changes in Incremental SO_x Emissions

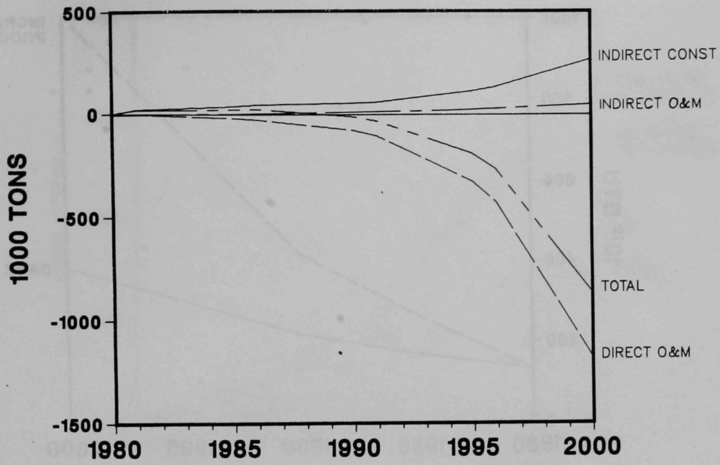

Fig. 3.15 Sensitivity Analysis of Solar Growth: Changes in Incremental NO_x Emissions

3.5 INCREASED ALCOHOL PRODUCTION FROM CORN

Both the 6-quad and 14-quad evaluations assumed that DOE/EIA[16] projected increases in alcohol fuel production to a level of 381×10^{12} Btu by the year 2000. (One gallon of alcohol, when upgraded by extractive distillation, has a heating value of 84,000 Btu.) An additional analysis was conducted to evaluate the impact on national air pollutant emissions of increasing this production to 10^{15} Btu (1 quad) by 2000 (Fig. 3.16). The use of a coal boiler to supply process heat, as defined in Refs. 11 and 15, was assumed as the standard technology. This technology, which is typical of that used in the beverage industry, requires 2.13 Btu from coal for each Btu of alcohol output. Also considered was a second design with improved efficiency, which requires 1.25 Btu input per Btu of alcohol produced.

With the requirement for process heat input exceeding the energy content of the output, and the assumption that coal is used for the input energy, the effect on air pollutant emissions of the increased alcohol production is significant. For example, national SO_2 emissions are increased by nearly 800,000 tons by the high-alcohol scenario in the year 2000 with the standard beverage industry technology, or by 460,000 tons with the improved technology. If this alcohol production is included as part of the high, 14-quad solar scenario, the net benefit in SO_2 emission, compared to the 6-quad scenario, is significantly reduced (Fig. 3.17).

Similarly, adding the high alcohol production to the 14-quad scenario increased the increment in particulate emissions, as compared to the 6-quad scenario, from 144,000 tons to 310,000 tons with the standard alcohol technology, or to 280,000 tons with the improved technology (Fig. 3.18). The change in NO_x emissions with the alcohol scenarios (Fig. 3.19) was to reduce the

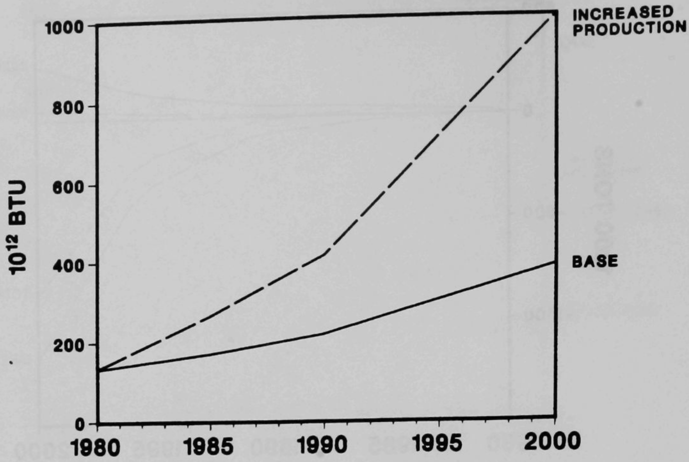

Fig. 3.16 Alcohol Production in Low-Solar and High-Solar Scenarios (Base) and Increased Production Assumed for Sensitivity Study of High-Solar Scenario

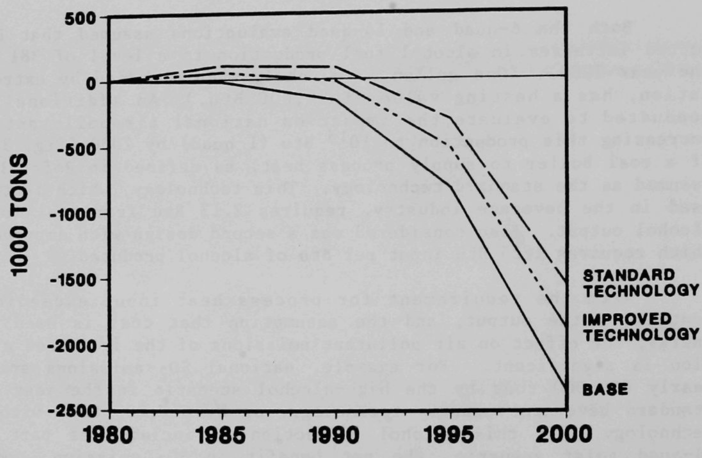

Fig. 3.17 Incremental SO_x Emissions: High-Solar Minus Low-Solar Scenario, with Equal Alcohol Production in Both (Base) and with Increased Alcohol Production in the High-Solar Scenario Using Two Different Technologies

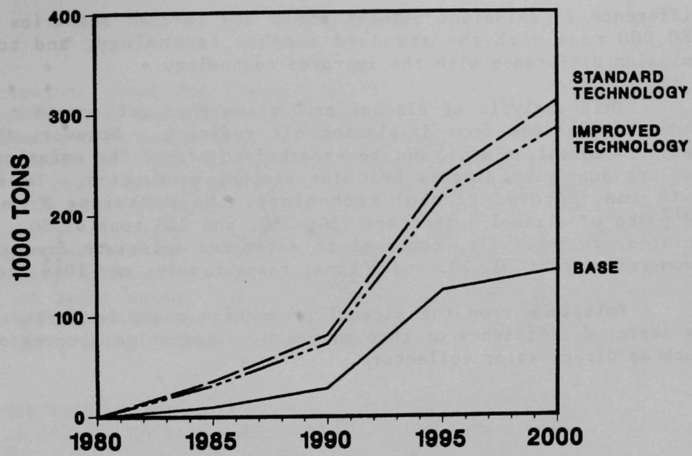

Fig. 3.18 Incremental Particulate Emissions: High-Solar Minus Low-Solar Scenario, with Equal Alcohol Production in Both (Base), and with Increased Alcohol Production in the High-Solar Scenario Using Two Different Technologies

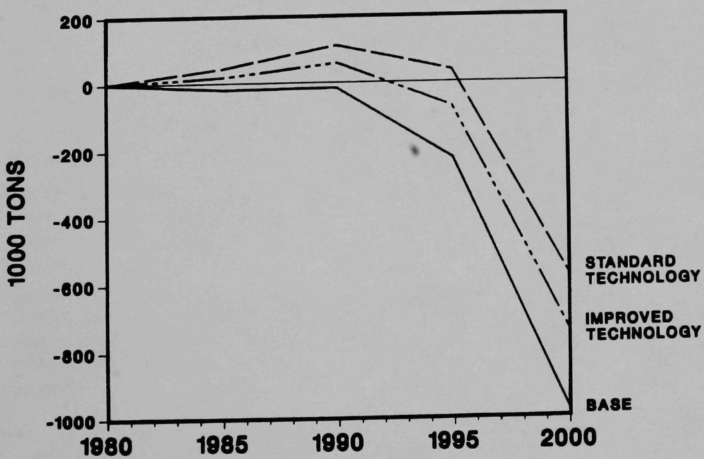

Fig. 3.19 Incremental NO_x Emissions: High-Solar Minus Low-Solar Scenario, with Equal Alcohol Production in Both (Base), and with Increased Alcohol Production in the High-Solar Scenario Using Two Different Technologies

difference in emissions between the 6 and 14-quad scenarios from 980,000 to 580,000 tons with the standard alcohol technology, and to a 742,000-ton emission difference with the improved technology.

This analysis of alcohol production does not consider the benefits in reduced emissions from displacing oil refining. However, the reduction in refinery emissions would not be expected to offset the emissions from the coal boilers supplying process heat for alcohol production. To illustrate, even with the improved alcohol technology, the emissions from coal used per 10^{12} Btu of alcohol output are 750, 380, and 230 tons of SO_x, NO_x, and particulates, respectively, compared to estimated emissions from catalytic petroleum refining of 70, 20, and 5 tons, respectively, per 10^{12} Btu.[22]

Emissions from the alcohol production could be further reduced either by improved efficiency or through use of alternative sources of process heat, such as direct solar collectors.

4 CONCLUSIONS

Conclusions about the feasibility of, costs of, and trade-offs among various technologies are given in an earlier TASE report.[15] General conclusions about the 6- and 14-quad solar scenarios are difficult to make. The first conclusion is that the 14-quad solar scenario is not a reasonable scenario. It provided a framework for studying the problems involved in the introduction of solar technologies into the energy-supply system of the United States, but the scenario itself calls for large amounts of energy from technologies that are not economical under the assumptions of the study. The sensitivity studies were able to begin to demonstrate how some of the advantages of solar energy could be retained without incurring unacceptably high costs or air-pollutant emissions. More work needs to be done on that aspect of the problem. Some conclusions about the 6- and 14-quad scenarios are:

- The capital-intensive nature of the solar technologies creates an increased demand for capital that reaches $20 billion per year by the year 2000, for a shift of 8 quads (fossil fuel equivalents) per year of energy from conventional sources to solar energy in the 14-quad scenario. The increase in capital costs is only partially offset by a decrease in operation and maintenance costs.
- The high-solar scenario yields significant net reductions in SO_x and NO_x (several percent of the national total for 1978) due to decreased direct emissions from fossil fuels, but a net increase in particulate emissions from both indirect construction emissions and direct emissions from the combustion of biomass. Nationally, the particulate increase is not significant, but local concentrations during the heating season could be a serious problem.
- By 2000, nearly 1 quad more fossil fuel is required per year for the high-solar scenario than for the low. This reduces by 15% the 6.5 quad of fossil fuel saved in the 14-quad scenario.
- Indirect air-pollutant emissions and employment from the construction of the capital-intensive solar facilities are significant during the period of high solar growth postulated between now and 2000 in the 14-quad solar scenario.

There is a trade-off to be made between capital costs and operating costs by residential/commercial and industrial consumers as well as by electric utilities. In light of the results presented here and those in the previous report,[15] it is clear that more study is required on how energy consumers make those trade-offs and on the effects of government actions, including taxation and regulation, on those trade-offs.

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